



Letters

Superior fatigue response of LENS-manufactured Ti-5553 alloy

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ABSTRACT

In this paper, fatigue performance of Ti-5553 alloy fabricated using Laser Engineered Net Shaping (LENS) was investigated. Mechanical testing revealed high tensile strength (UTS: 1377 MPa) and good ductility (16 %). Fatigue tests under fully reversed loading expose superior endurance, with crack initiation mechanisms transitioning from surface-induced at high stresses to internal defect-assisted at lower amplitudes. Fractography exposed unmelted particles as initiation sites under moderate cyclic loads. The results establish LENS as a reliable method for manufacturing high-strength Ti-5553 components for high-performance applications.

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1. Introduction

Titanium alloys, particularly near-beta compositions such as Ti-5Al-5Mo-5 V-3Cr (commonly known as Ti-5553), have gained significant interest in the aerospace and automotive industries due to their superior combination of high strength, excellent corrosion resistance, and good hardenability [1,2]. Ti-5553 is specifically engineered for high-performance structural applications where both, static and cyclic loading conditions, are critical [3,4]. Its high strength-to-weight ratio and high mechanical properties make it particularly suitable for landing gear components, fuselage frames, and high-load-bearing automotive parts, where fatigue resistance is paramount [5].

In recent years, the adoption of additive manufacturing (AM) technologies for fabricating titanium components has opened new possibilities for complex geometries, weight reduction, and tailored microstructures [6–22]. However, the fatigue performance of AM-fabricated Ti-5553 has emerged as a critical concern, primarily due to inherent process-induced defects such as porosity, surface roughness, and microstructural anisotropy [17,23]. These features act as stress concentrators and significantly influence crack initiation and propagation under cyclic loading [24]. Although several studies have investigated the tensile properties and heat-treatment responses of AM Ti-5553, its low-cycle fatigue behaviour remains less understood, especially in relation to speci-

fic AM processes and post-processing treatments. Ti-5553 manufactured by using Laser Powder Bed Fusion (LPBF) exhibited high density (>99.8 %) but still much lower fatigue performance compared to wrought/hot isostated pressed (HIP) material due to residual porosity and high surface roughness. Two-stage heat treatment, β annealing (super beta transus) and ageing increased hardness and tensile strength by promoting α -phase precipitation but reduced ductility. Fatigue strength was affected by surface roughness and porosity, which dominated over microstructural effects [19]. PBF-EB-manufactured Ti-5553 exhibited > 99.8 % density, but fatigue performance was well below conventionally processed material. Beta annealed, slow cooled and aged treated specimens outperformed solution treated and aged ones, with greater defect tolerance, yet both were highly sensitive to surface and subsurface defects. The study emphasised that relative density alone is not a reliable indicator of fatigue strength, as defect characteristics control fatigue life [25]. In cast and homogenised Ti-5553, β -annealed microstructures demonstrated superior low-cycle fatigue performance compared to bimodal microstructures despite similar yield strengths. The difference was attributed to cyclic softening behaviours and micro-crack/microstructure interactions [26]. LPBF Ti-5553 showed high strength (~1220 MPa UTS) with good ductility (~14 %), balancing properties compared to wrought alloys. Part location within the build had a limited influence on tensile or fatigue performance, despite defect distribution differences. Machining improved fatigue life but introduced greater scatter, highlighting the dominant role of surface roughness in crack initiation over volumetric defects [27]. One should highlight that among the various AM techniques, Direct Energy

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Deposition (DED) techniques offer unique advantages for the fabrication of high-performance titanium alloys [2]. They enable precise control over thermal input and solidification conditions, facilitating the production of dense, directionally solidified components with reduced residual stresses [2,7–9]. Moreover, the ability to control process parameters during layer-by-layer deposition provides opportunities to design the microstructure and texture in a location-specific manner [8,9], potentially improving fatigue performance. Unlike powder bed fusion methods, DED, or specifically LENS, also enables for the repair and hybrid manufacturing of large-scale components, making it particularly attractive for aerospace applications.

Despite recent advantages in the field, the fatigue behaviour of Ti-5553 produced via LENS remains underexplored. Most existing studies focus on other titanium alloys such as Ti-6Al-4 V, leaving a significant knowledge gap in understanding how LENS can be leveraged to optimize the cyclic performance of Ti-5553. This study aims to fill this gap by systematically investigating the fatigue behaviour of LENS-processed Ti-5553, with a focus on correlating process-induced microstructural features with fatigue life. Additionally, the work provides new insights into the potential of LENS to overcome traditional fatigue limitations in near-beta titanium alloys and lays the groundwork for process optimization in fatigue-critical applications. This paper follows the work reported in [28], where the authors explained the microstructural aspects of LENS-manufactured Ti-5553, with an emphasis on how such a microstructure enhances the yield and tensile strength of the material in question.

2. Materials and methods

Spherical Ti-5553 alloy powder, with particle sizes ranging from 45 to 106 μm , supplied by AP&C (a subsidiary of GE Additive), was employed in the fabrication of cylindrical samples using a LENS 850-R system (OPTOMECH, USA), which incorporates a 1 kW fiber laser source. Additive manufacturing was carried out through a layer-wise deposition strategy, producing cylindrical builds with a height of 100 mm and a diameter of 10 mm in a closed environment filled with argon gas with oxygen levels continuously monitored and maintained below 15 ppm, to prevent oxidation of metal parts. The processing parameters optimized for this build configuration are presented in Fig. 1.

Subsequent to the additive manufacturing process, specimens intended for mechanical characterization were extracted parallel to the build direction (Z-axis). Uniaxial tensile tests were performed on three individual samples using a servo-hydraulic MTS 858 test frame operated at a constant crosshead displacement rate of 0.01 mm/s. A high-precision MTS extensometer was used to monitor changes in the specimen diameter within a 4 mm gauge section. Axial strain was computed indirectly, based on transverse strain measurements and an assumed Poisson's ratio. From these tests, mechanical properties including the 0.2 % offset yield strength ($R_{0.2}$), ultimate tensile strength (R_m), and total elongation (%) were determined.

Fatigue behavior was assessed under fully reversed loading conditions (zero mean stress) using a force-controlled test mode. A constant stress amplitude was applied at a test frequency of 20 Hz, with the amplitude range (± 600 MPa to ± 1100 MPa) being determined relative to the measured yield strength. To ensure the reliability of the fatigue data and consistency of the additive manufacturing process, a minimum of three specimens was tested at each stress amplitude level. Following fatigue failure, fracture surface analysis was conducted using a JEOL JSM-6360LA scanning electron microscope.

3. Results and discussion

The mechanical performance of the LENS-fabricated Ti-5553 alloy was first assessed through uniaxial tensile testing along the build (Z) direction. As shown in Fig. 2a, the alloy demonstrated a yield strength of approximately 1198 MPa, an ultimate tensile strength of 1377 MPa, and a total elongation of 16 %. Enhanced mechanical properties were attributed to the presence of a multi-phase $\alpha + \beta$ morphology, ω -phase, and the α structure and its volume fraction [28]. The as-built Ti-5553 microstructure produced by LENS exhibited a multiphase $\alpha + \beta$ morphology with α precipitates both at β grain boundaries and as intragranular lamellar α , along with fine acicular secondary α and occasional Widmanstätten-type α due to repeated thermal cycling [28]. Additional microstructural characterization confirmed traces of nanometric ω . The identified ω -phase was interpreted as athermal, formed during rapid cooling, having a very low volume fraction. Its presence had only a limited embrittling effect, as reflected in the high strength and ductility of the as-built specimens. While

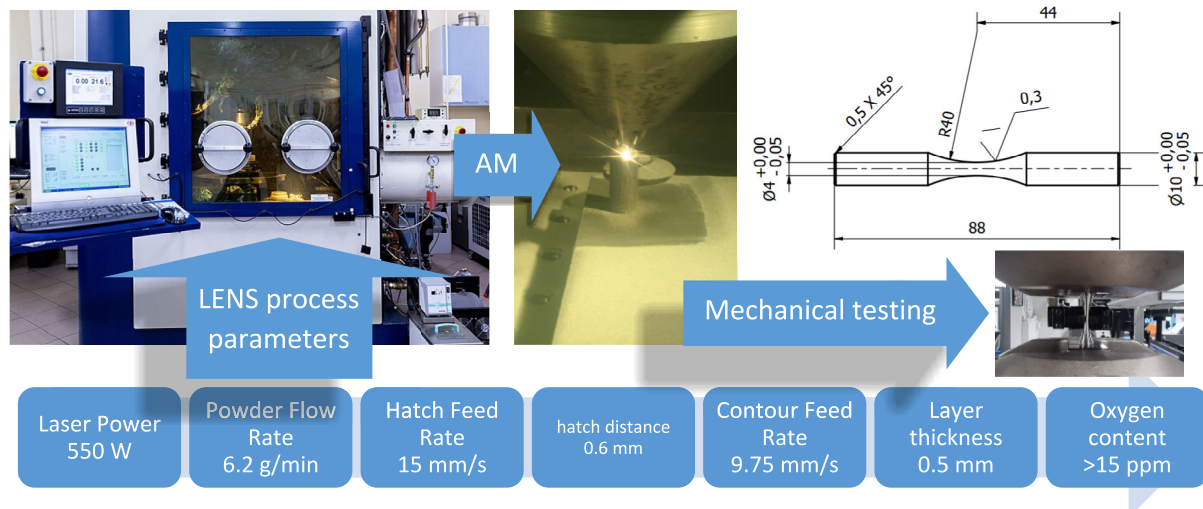


Fig. 1. Schematic of experimental programme.

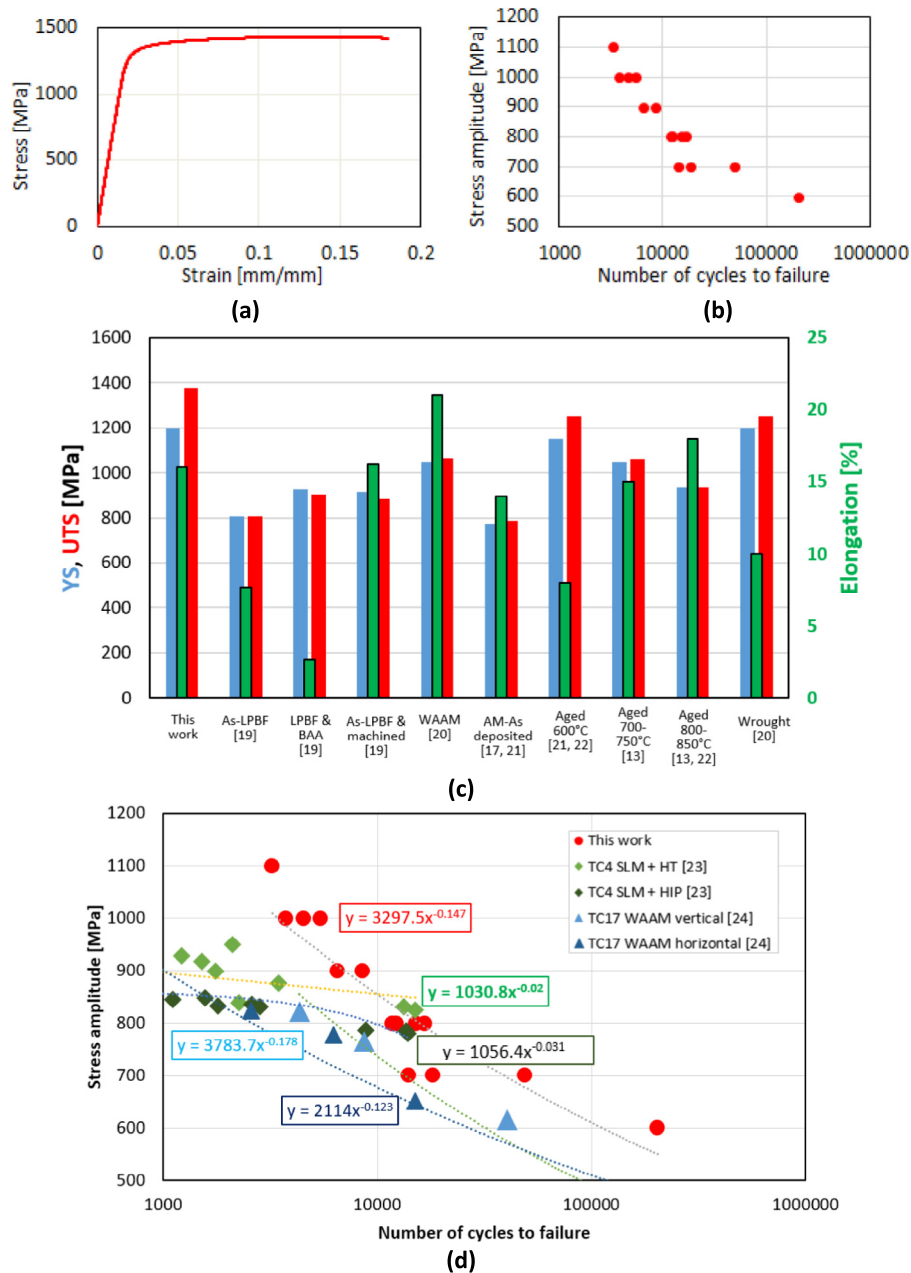


Fig. 2. Tensile characteristics (a); S-N curve (b); comparison of tensile (c) and fatigue (d) response of LENS Ti-5553 with reported works [13,17,19,20,21–24].

athermal ω provides minimal direct strengthening, it likely assisted the refinement of the α morphology by acting as a precursor for α precipitation. Furthermore, the uniform distribution of α phase throughout the material volume reduces precipitation-free regions within the β matrix phase. Therefore, the α phase hinders dislocation motion during deformation, thus effectively improving materials tensile and yield strength. The strength levels achieved in this work indicate that the LENS process can produce a relatively fine scale of the β grains and the homogeneous dispersion of intragranular α precipitates within the β matrix with minimal detrimental porosity or unmelted regions. Within these β grains, fragmented α_p and ultrafine acicular α_s precipitates are present [28], creating a refined substructure that enhances mechanical performance [8]. Furthermore, the elongation to failure was also relatively high, suggesting that the process parameters used (e.g., laser power, scanning speed, and powder feed rate) were sufficiently optimized to minimize interlayer defects and residual stress

accumulation. Moreover, the mechanical behavior confirms that despite the inherent thermal gradients and directional solidification associated with LENS, the process can achieve competitive or superior tensile performance compared to wrought or SLM-fabricated counterparts.

The fatigue performance of the LENS-processed Ti-5553 alloy was evaluated under fully reversed, force-controlled cyclic loading at various stress amplitudes. The resulting S-N data are plotted in Fig. 2b. The fatigue life demonstrated a strong inverse relationship with applied stress amplitude. At high stress amplitudes (e.g., ± 1100 MPa), failure occurred rapidly (within $< 10^3$ cycles), indicating dominance of low-cycle fatigue (LCF) mechanisms. In contrast, at reduced amplitudes (e.g., ± 600 MPa), the fatigue life increased significantly, exceeding 10^5 cycles and approaching the high-cycle fatigue (HCF) regime.

The fatigue life and tensile performance of the LENS-processed samples were then compared with data from the literature on

Ti-5553 alloys processed via conventional metallurgy, SLM, and wire-arc additive manufacturing (WAAM), as shown in Fig. 2c and 2d. Notably, the present study demonstrates a competitive fatigue life relative to both conventionally forged Ti-5553 and other AM variants, particularly those using SLM [17,20,21]. This improved performance can be attributed to several factors involving reduced porosity and defect content, columnar β -grain alignment and thermal management. The LENS process enables real-time control over laser parameters and powder feed rate, which minimizes the formation of keyhole pores, lack-of-fusion defects, and solidification cracking—all of which are known fatigue initiators. Additionally, directional solidification along the build axis may lead to columnar β grains, which can potentially delay crack propagation if aligned favorably with the loading direction. Furthermore, the use of interlayer cooling and optimized scanning strategies likely contributed to reduced residual stress gradients and more uniform phase distribution, promoting fatigue resistance. Compared to SLM-produced Ti-5553, which typically suffers from fine-scale porosity and complex residual stress patterns, LENS-fabricated parts appear to maintain a better balance of ductility and fatigue endurance. Furthermore, when compared with WAAM, the finer microstructural control and lower heat input per unit volume in LENS enable fabrication of near-net-shape parts with superior surface integrity.

Subsequently, the data was analysed in terms of Basquin theory [29] using the following equation:

$$S = AN_f^B \quad (1)$$

where S is the measure of stress, N_f is the number of cycles to failure, and A and B are the stress–life coefficient and exponent, respectively. The material in question was characterized by the highest fatigue strength coefficients of approx. 3297.5 and -0.147 . This combination highlights its exceptional performance in the low-cycle regime, where stress amplitudes exceeded 1000 MPa. However, the relatively steep exponent also implies that the material's fatigue strength decreases more rapidly as the number of cycles increases, thus limiting its long-life fatigue performance. Such an issue should be further investigated during high-cycle fatigue tests. One can observe that the TC4 alloy produced by SLM followed by heat treatment, shows a coefficient of approximately 1030.8 and an exponent of -0.02 [23]. Such a lower exponent value indicates a nearly flat slope and stable fatigue resistance over a wide range of cycles; however, with a lower initial strength. Similarly, the HIP-treated TC4 alloy was characterized by an almost linear trend with a negligible slope corresponding to a fatigue strength coefficient of about 863 MPa and a near-zero exponent. This confirms that HIP provides outstanding resistance against fatigue degradation by minimising defects, even though the short-life strength is lower than in the current study [23]. The TC17 alloy produced by WAAM demonstrates inferior fatigue resistance, with fatigue strength coefficients of 3783.7 and 2114 for vertically and horizontally tested samples, respectively [24]. Although the vertical orientation is characterised by a high stress during LCF, its exponent is the steepest of all conditions, leading to a rapid decline in strength with cycles. The horizontally tested WAAM material shows a less steep slope but remains less competitive than SLM-based materials across the analysed stress amplitude range.

The fracture surfaces of LENS-processed Ti-5553 specimens subjected to cyclic loading were investigated using SEM to elucidate fatigue initiation and propagation mechanisms across various applied stress amplitudes (Fig. 3). Particular attention was given to the interaction between process-induced microstructural features and the local fracture morphology. For specimens tested at stress amplitudes below 1000 MPa—including the critical cases at ± 700 MPa and ± 600 MPa—crack initiation was consistently

observed to occur from internal defects rather than obvious surface-connected flaws (Fig. 3c and 3d). These initiation sites were typically associated with unmelted or partially fused powder particles embedded within the matrix, suggesting incomplete local fusion during LENS processing.

Notably, these unmelted particles were often surrounded by a thin interfacial gap or oxide shell, creating local stress concentrations under cyclic loading. SEM imaging revealed that the crack origin frequently coincided with the interface between the matrix and these inclusions, where a combination of thermal mismatch, poor bonding, and mechanical discontinuity created favorable conditions for early microcrack formation. This mechanism of internal defect-assisted crack initiation is consistent with recent findings in other DED-processed titanium alloys, where such flaws are often present due to complex melt pool dynamics and insufficient remelting during layer deposition [8,9,24]. The subsurface nature of these initiation sites was confirmed by the presence of concentric crack front markings (reminiscent of “fish-eye” patterns) radiating from an internal origin, as well as the absence of obvious surface-breaking flaws. These observations strongly indicate that internal inclusions play a dominant role in fatigue initiation under moderate cyclic stresses, where surface roughness effects are reduced and bulk integrity becomes the primary life-limiting factor. A clear transition in the dominant crack initiation mechanism was observed as a function of applied stress amplitude.

At high stress amplitudes (≥ 1000 MPa), fatigue cracks initiated predominantly at or near the surface, where micro-notches and topographic features acted as stress concentrators. These surface-initiated cracks often coalesced quickly with subsurface defects, leading to rapid failure dominated by quasi-cleavage features and localized facetting (Fig. 3a and 3b). At intermediate to low amplitudes (< 1000 MPa), the crack initiation shifted inward, with internal defects—particularly unmelted particles and isolated pores—serving as the primary origins. The crack initiation transition from the surface to the interior is attributed to the defect size and the applied stress value. One should highlight that in the LCF regime, where stress exceeds the YS , even small surface and geometrical notches act as effective stress concentrators. As they accelerate the reaching of the crack initiation threshold, the surface features are thus dominant sites for crack formation and propagation. On the other hand, the decrease in the applied stress reduces the effect of surface features on limiting the service life of the tested components. Under lower stress amplitude, larger internal defects such as unmelted particles or isolated pores become critical, since the critical defect size required to initiate a crack increases with decreasing applied stress. Consequently, subsurface defects, often shielded from surface oxidation and environmental assistance, provide the necessary defect size and local stress concentration for crack initiation, leading to the observed inward shift at intermediate to low amplitudes [30]. These sites were not readily visible from the surface, suggesting that such flaws may be found below the topmost layer, likely formed during earlier deposition cycles. At lower stresses, surface defects may no longer reach this threshold, thereby elevating the significance of larger, though less frequent, internal flaws. This phenomenon emphasizes the need for volumetric quality control in LENS-fabricated parts—not just surface finishing—when fatigue resistance is required at moderate loading levels. Following initiation, fatigue cracks propagated via transgranular mechanisms, with clear evidence of fatigue striations and secondary cracking at lower amplitudes (Fig. 3c and 3d). The striation spacing was finer compared to that observed at higher stress levels, in accordance with decreasing crack growth rates. The propagation zones expanded in width and complexity as the number of cycles increased, reflecting stable fatigue crack growth over an extended lifetime. Striation morphology also showed slight variations near the origin sites of unmelted particle defects, where the local stress

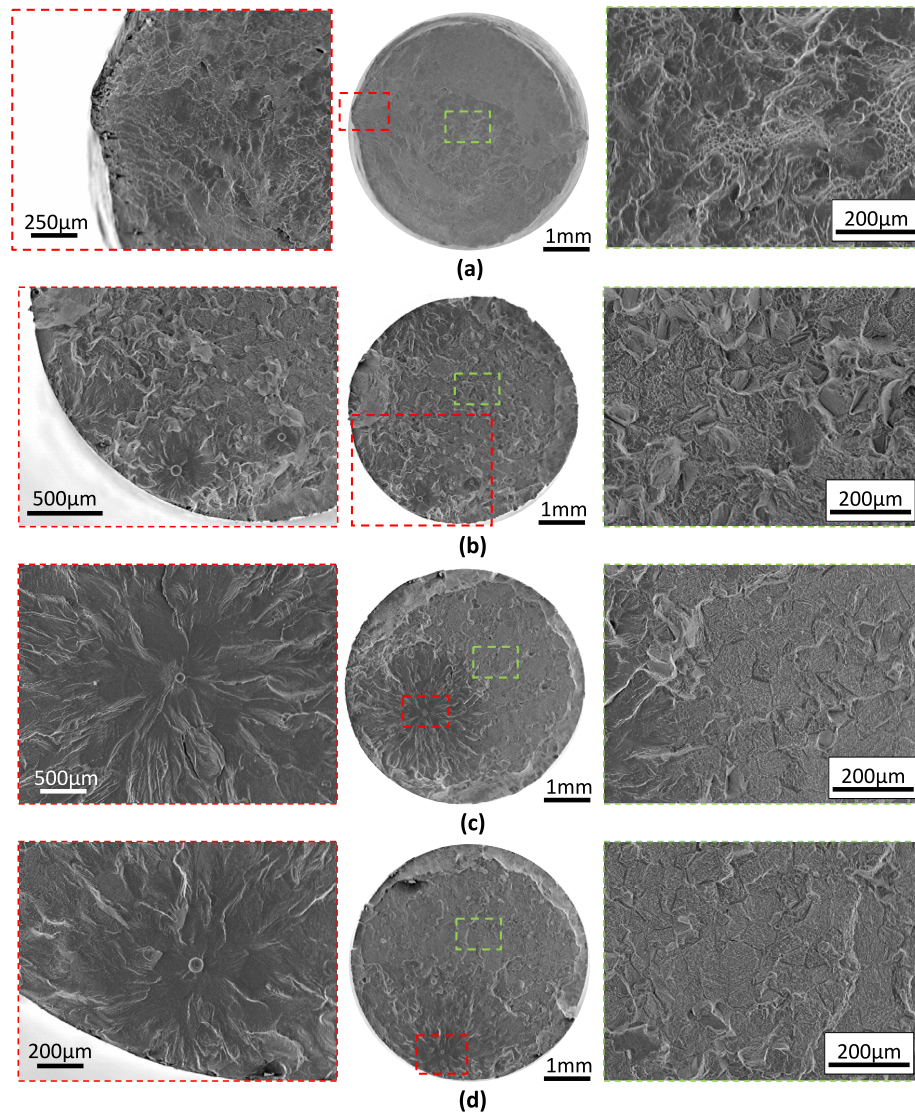


Fig. 3. Fracture surfaces of LENS-manufactured Ti-5553 subjected to stress amplitudes of 1100 MPa (a); 1000 MPa (b), 700 MPa (c) and 600 MPa (d).

field perturbation and interfacial decohesion may have introduced additional crack branching and deflection. Moreover, the lack of crack deflection in the fracture path implies that grain boundary α -phase, often a weak link in cyclic loading, was either absent or present in discontinuous form. This is beneficial for fatigue resistance, as continuous grain boundary α has been shown to serve as an easy crack propagation pathway in β -Ti alloys subjected to cyclic loading [15,18].

4. Conclusions

This study demonstrates that the LENS process can produce Ti-5553 alloy components with excellent mechanical and fatigue properties. The fabricated material exhibited a high yield strength of 1198 MPa, an ultimate tensile strength of 1377 MPa, and a total elongation of 16 %, highlighting the process's capability to retain ductility while achieving elevated strength levels. Under fully reversed cyclic loading, the alloy showed a clear stress-dependent fatigue response, transitioning from low-cycle fatigue at high stress amplitudes (± 1100 MPa) to high-cycle fatigue with

lives exceeding 105 cycles at lower amplitudes (± 600 MPa). Fractographic analysis revealed a shift in crack initiation mechanism with decreasing stress: while surface-connected features dominated initiation at high loads, internal defects—particularly unmelted powder particles—were the primary sources of crack initiation at lower stresses. These defects created local stress concentrations and interfacial decohesion, accelerating microcrack formation and early fatigue failure. Crack propagation proceeded via transgranular mechanisms with well-defined striations and ductile final fracture zones, suggesting stable crack growth and retained toughness.

CRediT authorship contribution statement

Mateusz Kopec: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Tomasz Durejko:** Validation, Resources, Methodology, Investigation, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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